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Measurement of Time-Dependent CP Asymmetries and the CP-Odd Fraction in the Decay $B^0 \to D^{*+}D^{*-}$

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We present an updated measurement of time-dependent *CP* asymmetries and the *CP*-odd fraction in the decay $B^0 \to D^{*+}D^{*-}$ using $232 \times 10^6 B\overline{B}$ pairs collected by the *BABAR* detector at the PEP-II *B* factory. We determine the *CP*-odd fraction to be $0.125 \pm 0.044(\mathrm{stat}) \pm 0.007(\mathrm{syst})$. The time-dependent *CP* asymmetry parameters C_+ and S_+ are determined to be $0.06 \pm 0.17(\mathrm{stat}) \pm 0.03(\mathrm{syst})$ and $-0.75 \pm 0.25(\mathrm{stat}) \pm 0.03(\mathrm{syst})$, respectively. The Standard Model predicts these parameters to be 0 and $-\sin 2\beta$, respectively, in the absence of penguin amplitude contributions.

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The time-dependent *CP* asymmetry measurement in $B^0 \to D^{*+}D^{*-}$ decay provides an important test of the Standard Model (SM). In the SM, *CP* violation arises from a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. Measurements of *CP* asymmetries by the *BABAR* [2] and BELLE [3] collaborations have firmly established this effect in the $B^0 \to J/\psi K^0_S$ decay [4] and related modes that are governed by the $b \to c\bar{c}s$ transition. The $B^0 \to D^{*+}D^{*-}$ decay is dominated by the $\to c\bar{c}d$ transition. Within the framework of the SM, the *CP* asymmetry of $B^0 \to D^{*+}D^{*-}$ is related to $\sin 2\beta$ when the correction due to penguin diagram contributions are neglected. The penguin-induced correction has been estimated in models based on the factorization approximation and heavy quark symmetry and was predicted to be about 2% [5]. A significant deviation of the measured $\sin 2\beta$ from the one observed in $b \to c\bar{c}s$ decays would be evidence for a new *CP*-violating interaction. The enhanced sensitivity of $B^0 \to D^{*+}D^{*-}$ to such a process arises from its much smaller SM amplitude compared with that of the $b \to c\bar{c}s$ transition.

The $B^0 \to D^{*+}D^{*-}$ decay proceeds through the *CP*-even S and D waves and through the *CP*-odd P wave. In this Letter, we present an improved measurement of the *CP*-odd fraction [6, 7] $R_\perp$ based on a time-integrated one-dimensional angular analysis. We also present an improved measurement of the time-dependent *CP* asymmetry [6, 7], obtained from a combined analysis of time-dependent flavor-tagged decays and the one-dimensional angular distribution of the decay products.

The data used in this analysis comprise 232 million $\Upsilon(4S) \to B\overline{B}$ decays collected by the *BABAR* detector at the PEP-II storage ring. The *BABAR* detector is described in detail elsewhere [8]. We use a Monte Carlo (MC) simulation based on GEANT4 [9] to validate the analysis procedure and to study the relevant backgrounds.

We select $B^0 \to D^{*+}D^{*-}$ decay by combining two charged D^* candidates reconstructed in the modes $D^{*+} \to D^0\pi^+$ and $D^{*+} \to D^+\pi^0$. We include the $D^{*+}D^{*-}$ combinations $(D^0\pi^+, \overline{D}^0\pi^-)$ and $(D^0\pi^+, D^-\pi^0)$, but not $(D^+\pi^0, D^-\pi^0)$ because of the smaller branching fraction and larger backgrounds. To suppress the $e^+e^- \to q\bar{q}$ ($q = u, d, s$, and c) continuum background, we require the ratio of the second and zeroth order Fox-Wolfram moments [10] to be less than 0.6.

Candidates for D^0 and D^+ mesons are reconstructed in the modes $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^0_S\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$, $K^0_S\pi^+$, $K^-K^+\pi^+$. The reconstructed mass of the D^0 (D^+) candidate is required to be within 20 MeV/c^2 of its nominal mass [11], except for the $D^0 \to K^-\pi^+\pi^0$ candidate, where a looser requirement of 40 MeV/c^2 is applied.

The K^0_S candidates are reconstructed from two oppositely-charged tracks with an invariant mass within 20 MeV/c^2 of the nominal K^0_S mass. The χ^2 probability of the $\pi^+\pi^-$ vertex fit must be greater than 0.1 %. Charged kaon candidates are required to be inconsistent with the pion hypothesis, as inferred from the Cherenkov angle measured by the Cherenkov detector and the ionization energy loss measured by the charged-particle tracking system. Neutral pion candidates are formed from two photons detected in the electromagnetic calorimeter, each with energy above 30 MeV. The mass of the pair must be within 30 MeV/c^2 of the nominal π^0 mass, and their summed energy is required to be greater than 200 MeV. In addition, a mass-constrained fit is applied to the π^0 candidates for further analysis.

The D^0 and D^+ candidates are subject to a mass-constrained fit prior to the formation of the D^{*+} candidates. A slow π^+ from D^{*+} decay is required to have a momentum in the $\Upsilon(4S)$ center-of-mass (CM) frame less than 450 MeV/c. A slow π^0 from D^{*+} must have a momentum between 70 and 450 MeV/c in the CM frame. No requirement on the photon-energy sum is applied to the π^0 candidates from the D^{*+} decays.

For each $B^0 \to D^{*+}D^{*-}$ candidate, we construct a likelihood function [12] $\mathcal{L}_{\mathrm{mass}}$ from the masses and mass uncertainties of the D and D^* candidates. The likelihood $\mathcal{L}_{\mathrm{mass}}$ is calculated as the product of the likelihoods for the D and D^* candidates. The D mass resolution is modeled by a Gaussian whose variance is determined on a candidate-by-candidate basis. The D^*-D mass difference resolution is modeled by a double-Gaussian distribution whose parameters are determined from simulated events. The values of $\mathcal{L}_{\mathrm{mass}}$ and the difference of the B^0 candidate energy E_B from the beam energy E_{Beam},

$\Delta E \equiv E_B - E_{\rm Beam}$, in the $\Upsilon(4S)$ CM frame are used to reduce the combinatoric background further. From the simulated events, the maximum allowed values of $-\ln\mathcal{L}_{\rm mass}$ and $|\Delta E|$ are optimized for each individual final state to obtain the highest expected signal significance using the previously measured $B^0 \to D^{*+}D^{*-}$ branching fraction [6].

The energy-substituted mass, $m_{\rm ES} \equiv \sqrt{E^2_{\rm Beam} - p^{*2}_B}$, where p^*_B is the B^0 candidate momentum in the $\Upsilon(4S)$ CM frame, is used to extract the signal yield from the events satisfying the aforementioned selection. We select the B^0 candidates that have $m_{\rm ES} \geq 5.23$ GeV/c^2. In cases where more than one B^0 candidate is reconstructed in an event, the candidate with the smallest value of $-\ln\mathcal{L}_{\rm mass}$ is chosen. A fit to the $m_{\rm ES}$ distribution with a probability density function (PDF) given by the sum of a Gaussian shape for the signal and an ARGUS [13] function for the background yields 391 ± 28(stat) signal events. In the region of $m_{\rm ES} > 5.27$ GeV/c^2, the signal purity is approximately 70 %.

In the transversity basis [14], we define the following three angles: the angle θ_1 between the momentum of the slow pion from the D^{*-} and the opposite direction of flight of the D^{*+} in the D^{*-} rest frame; the polar angle $\theta_{\rm tr}$ and azimuthal angle $\phi_{\rm tr}$ of the slow pion from the D^{*+} defined in the D^{*+} rest frame, where the opposite direction of flight of the D^{*-} is chosen as the x-axis, and the z-axis is defined as the normal to the D^{*-} decay plane.

The time-dependent angular distribution of the decay products is given in Ref. [15]. Taking into account the detector angular acceptance efficiency and integrating over the decay time and the angles θ_1 and $\phi_{\rm tr}$, we obtain a one-dimensional differential decay rate:

$$\begin{aligned}\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm tr}} &= \frac{9}{32\pi}\Big[(1-R_\perp)\sin^2\theta_{\rm tr} \\ &\times \left\{\frac{1+\alpha}{2}I_0(\cos\theta_{\rm tr}) + \frac{1-\alpha}{2}I_\parallel(\cos\theta_{\rm tr})\right\} \\ &+ 2R_\perp\cos^2\theta_{\rm tr}\times I_\perp(\cos\theta_{\rm tr})\Big]\,, \qquad (1)\end{aligned}$$

where $R_\perp = |A_\perp|^2/(|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2)$, $\alpha = (|A_0|^2 - |A_\parallel|^2)/(|A_0|^2 + |A_\parallel|^2)$, A_0 is the amplitude for longitudinally polarized D^*s, $A_\parallel$ and $A_\perp$ are the amplitudes for parallel and perpendicular transversely polarized D^*s. The three efficiency moments, I_k $(k = 0, \parallel, \perp)$, are defined as

$$I_k(\cos\theta_{\rm tr}) = \int d\!\cos\theta_1\, d\phi_{\rm tr}\; g_k(\theta_1,\phi_{\rm tr})\,\varepsilon(\theta_1,\theta_{\rm tr},\phi_{\rm tr}), \quad (2)$$

where $g_0 = 4\cos^2\theta_1\cos^2\phi_{\rm tr}$, $g_{||} = 2\sin^2\theta_1\sin^2\phi_{\rm tr}$, $g_\perp = \sin^2\theta_1$, and ε is the detector efficiency. The efficiency moments are parameterized as second-order even polynomials of $\cos\theta_{\rm tr}$. Their parameter values are determined from the MC and are subsequently fixed in the likelihood fit to the differential decay distribution of $\cos\theta_{\rm tr}$. In fact, the three I_k functions deviate only slightly from a constant, making the distribution, Eq. 1, nearly independent of the amplitude ratio α.

The CP-odd fraction $R_\perp$ is measured in a simultaneous unbinned maximum likelihood fit to the $\cos\theta_{\rm tr}$ and the $m_{\rm ES}$ distribution. The background shape is modeled as an even second-order polynomial in $\cos\theta_{\rm tr}$, while the signal PDF is given by Eq. 1. The finite detector resolution of the $\theta_{\rm tr}$ measurement is modeled as a double Gaussian plus a small tail component that accounts for misreconstructed events. The parameterization of the $\theta_{\rm tr}$ resolution function is fixed from the MC simulation and subsequently used to convolve the signal PDF in the maximum likelihood fit. Since the angle $\theta_{\rm tr}$ is calculated with the slow pion from the D^{*+}, we categorize events into three types: $D^{*+}D^{*-} \to (D^0\pi^+, \overline{D}^0\pi^-)$, $(D^0\pi^+, D^-\pi^0)$, and $(D^+\pi^0, \overline{D}^0\pi^-)$, each with different signal-fraction parameters in the likelihood fit. Their angular efficiency moments and $\cos\theta_{\rm tr}$ resolutions are also separately determined from the MC simulation. The other parameters determined in the likelihood fit are the $\cos\theta_{\rm tr}$ background-shape parameter, three $m_{\rm ES}$ parameters (σ and mean of the signal Gaussian, and the ARGUS shape parameter κ), as well as $R_\perp$. The fit to the data yields

$$R_\perp = 0.125 \pm 0.044({\rm stat}) \pm 0.007({\rm syst}). \qquad (3)$$

The projections of the fitted result onto $m_{\rm ES}$ and $\cos\theta_{\rm tr}$ are shown in Fig. 1.

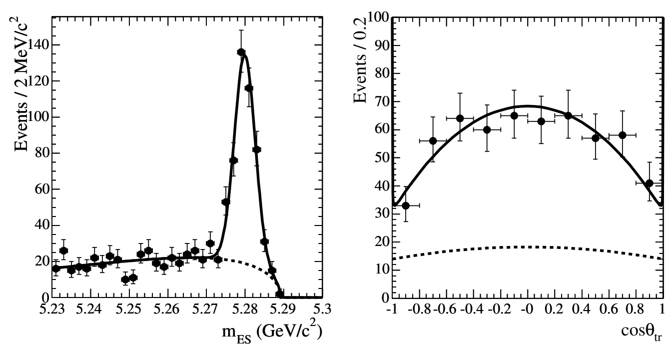

FIG. 1: Measured distribution of $m_{\rm ES}$ (left) and of $\cos\theta_{\rm tr}$ in the region $m_{\rm ES} > 5.27$ GeV/c^2 (right). The solid line is the projection of the fit result. The dotted line represents the background component.

In the fit described above, the value of α is fixed to zero. We estimate the corresponding systematic uncertainty by varying its value from -1 to $+1$ and find negligible change (less than 0.002) in the fitted value of $R_\perp$. Other systematic uncertainties arise from the parameterization of the angular resolution, the determination of the efficiency moments, and the background parameterization. The total systematic uncertainty on $R_\perp$ is 0.007, significantly smaller than the statistical error.

We subsequently perform a combined analysis of the $\cos\theta_{\rm tr}$ distribution and the time dependence to extract the time-dependent *CP* asymmetry, using the event sample described previously. We use information from the other B meson in the event to tag the initial flavor of the fully reconstructed $B^0 \to D^{*+}D^{*-}$ candidate.

The decay rate $f_+(f_-)$ for a neutral B meson accompanied by a $B^0(\overline{B}^0)$ tag is given by

$$f_\pm(\Delta t, \cos\theta_{\rm tr}) \propto {\rm e}^{-|\Delta t|/\tau_{B^0}} \Big\{ G(1 \mp \Delta\omega) \mp (1-2\omega) \\ [F \sin(\Delta m_d \Delta t) + H \cos(\Delta m_d \Delta t)] \Big\}, \quad (4)$$

where $\Delta t = t_{\rm rec} - t_{\rm tag}$ is the difference between the proper decay time of the reconstructed B meson ($B_{\rm rec}$) and that of the tagging B meson ($B_{\rm tag}$), τ_{B^0} is the B^0 lifetime, and Δm_d is the mass difference determined from the B^0-$\overline{B}^0$ oscillation frequency [11]. The average mistag probability ω describes the effect of incorrect tags, and $\Delta\omega$ is the difference between the mistag rate for B^0 and $\overline{B}^0$. The G, F and H coefficients are defined as:

$$\begin{aligned} G &= (1-R_\perp)\sin^2\theta_{\rm tr} + 2R_\perp \cos^2\theta_{\rm tr}, \\ F &= (1-R_\perp)S_+ \sin^2\theta_{\rm tr} - 2R_\perp S_\perp \cos^2\theta_{\rm tr}, \quad (5) \\ H &= (1-R_\perp)C_+ \sin^2\theta_{\rm tr} + 2R_\perp C_\perp \cos^2\theta_{\rm tr}, \end{aligned}$$

where we allow the three transversity amplitudes to have different $\lambda_k = (q/p)(\bar{A}_k/A_k)$ $(k = 0, \|, \perp)$ [15] due to possibly different penguin-to-tree amplitude ratios, and define the *CP* asymmetry $C_k = 1 - |\lambda_k|^2/1 + |\lambda_k|^2$, $S_k = 2\Im(\lambda_k)/1 + |\lambda_k|^2$. Here we also have:

$$C_+ = \frac{C_\| |A_\||^2 + C_0|A_0|^2}{|A_\||^2 + |A_0|^2}, S_+ = \frac{S_\| |A_\||^2 + S_0|A_0|^2}{|A_\||^2 + |A_0|^2}. \quad (6)$$

In the absence of penguin contributions, we expect that $C_0 = C_\| = C_\perp = 0$, and $S_0 = S_\| = S_\perp = -\sin 2\beta$.

In Eq. 4, the small angular acceptance effects are not taken into account and the *CP*-odd fraction is allowed to float in the final fit. No bias is seen in the resulting values of C_+, $C_\perp$, S_+, and $S_\perp$ in MC simulation. Hence, a dedicated method to correct the detector efficiency is not required. However, the "effective" value of $R_\perp$ obtained in this way is not identical to the value measured from the time-integrated analysis that includes the acceptance correction.

The technique used to measure the *CP* asymmetry is analogous to previous *BABAR* measurements as described in Ref. [16]. Only events with a Δt uncertainty less than 2.5 ps and a measured $|\Delta t|$ less than 20 ps are accepted. We performed a simultaneous unbinned maximum likelihood fit to the $\cos\theta_{\rm tr}$, Δt, and $m_{\rm ES}$ distributions to extract the *CP* asymmetry. The signal PDF in $\theta_{\rm tr}$ and Δt is given by Eq. 4. The signal mistag probability is determined from a sample of neutral B decays to flavor eigenstates, $B_{\rm flav}$. In the likelihood fit, the expression in Eq. 4 is convolved with an empirical Δt resolution function determined from the $B_{\rm flav}$ sample. The $\theta_{\rm tr}$ resolution is accounted for in the same way as described previously.

The background Δt distributions are parameterized with an empirical description that includes prompt and non-prompt components. We allow the non-prompt background to have two free parameters, $C_{\rm eff}$ and $S_{\rm eff}$, the effective *CP* asymmetries, in the likelihood fit. The background shape in $\theta_{\rm tr}$ is modeled as an even second-order polynomial in $\cos\theta_{\rm tr}$, much as it is in the time-integrated angular analysis.

The fit to the data yields

$$\begin{aligned} C_+ &= 0.06 \pm 0.17({\rm stat}) \pm 0.03({\rm syst}), \\ C_\perp &= -0.20 \pm 0.96({\rm stat}) \pm 0.11({\rm syst}), \\ S_+ &= -0.75 \pm 0.25({\rm stat}) \pm 0.03({\rm syst}), \\ S_\perp &= -1.75 \pm 1.78({\rm stat}) \pm 0.22({\rm syst}). \quad (7) \end{aligned}$$

Fig. 2 shows the Δt distributions and asymmetries in yields between B^0 and $\overline{B}^0$ tags, overlaid with the projection of the likelihood fit result. Because the *CP*-odd fraction is small, we have rather large statistical uncertainties for the measured $C_\perp$ and $S_\perp$ values. For comparison, we repeat the fit with the assumption that both *CP*-even and *CP*-odd states have the same *CP* asymmetry. We find that $C_+ = C_\perp = 0.03 \pm 0.13({\rm stat}) \pm 0.02({\rm syst})$, and $S_+ = S_\perp = -0.69 \pm 0.23({\rm stat}) \pm 0.03({\rm syst})$. In both cases, the effective *CP* asymmetries in the background are found to be consistent with zero within the statistical uncertainties.

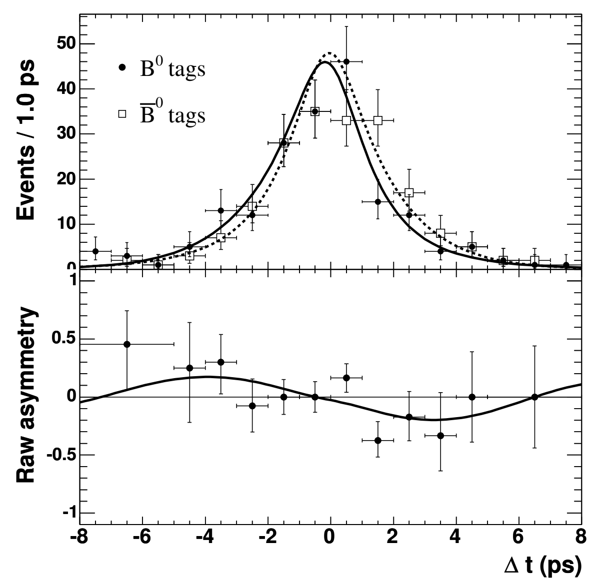

FIG. 2: From top to bottom: the distribution of Δt in the region $m_{\rm ES} > 5.27$ GeV/c^2 for B^0 ($\overline{B}^0$) tag candidates, and the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt. In the upper plot the solid (dashed) curves represent the fit projections in Δt for B^0 ($\overline{B}^0$) tags.

The systematic uncertainties on C_+, $C_\perp$, S_+ and $S_\perp$ arise from the amount of possible backgrounds that tend to peak under the signal and their *CP* asymmetry, the assumed parameterization of the Δt resolution function, the possible differences between the $B_{\rm flav}$ and B_{CP} mistag fractions, knowledge of the event-by-event beam-spot position, and the possible interference between the suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude and the favored $b \to c\bar{u}d$ amplitude for some tag-side decays [17]. It also includes the systematic uncertainties from the finite MC sample used to verify the fitting method. In general, all of the systematic uncertainties are found to be much smaller than the statistical uncertainties.

In summary, we have reported measurements of the *CP*-odd fraction and time-dependent *CP* asymmetries for the decay $B^0 \to D^{*+}D^{*-}$. The measurement supersedes the previous *BABAR* result [6], with more than 50 % reduction in the statistical uncertainty, and indicates that $B^0 \to D^{*+}D^{*-}$ is mostly *CP*-even. The time-dependent asymmetries are found to be consistent with the SM predictions within the statistical uncertainty.

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